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LEVEL II

SHIP FLEXURE MEASUREMENTS

by

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Research Department

August 1975

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Various applications in the past have led to the development of several optical alignment systems. More recently an electrooptic alignment system which is insensitive to angular displacements has been built. It consists of an intensity-modulated laser, a lens and a Schottky barrier position-sensing photodiode. Another afocal lens system with unit magnification has been developed to monitor displacement and tilt of an object moving in a straight line; however, it either measures displacement and is unaffected by tilt or measures tilt and is unaffected by displacement. Therefore, two assemblies need to be mounted side by side in a common block to measure tilt and displacement simultaneously.

This report describes a ship flexure monitoring system which has been developed to measure four degrees of freedom simultaneously. This system does not measure roll, the fifth degree of freedom; however, by using a polarizer or half-wave plate and detecting polarization changes, roll measurements can be incorporated.

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FOREWORD

This report has been prepared for the timely presentation of information on the analytical and experimental results of the ship flexure measurements of the U.S.S. Wainwright. The feasibility of this project was successfully demonstrated with actual data of ship flexure. The report gives preliminary findings of the study and is released at the working level for information only. This is a final report and concludes the optical flexure measurement project.

This research and development effort was performed for the period August 1974 through April 1975, supported by the Naval Sea Systems Command, CNO Project-D/694, Task No. UF00-344-402, Missile Reference System.

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14 July 1975

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INTRODUCTION

Various applications in the past have led to the development of several optical alignment systems.[1-4] More recently an electrooptic alignment system which is insensitive to angular displacements has been built.[5] It consists of an intensity-modulated laser, a lens and a Schottky barrier position-sensing photodiode. Another afocal lens system[6] with unit magnification has been developed to monitor displacement and tilt of an object moving in a straight line; however, it either measures displacement and is unaffected by tilt or measures tilt and is unaffected by displacement. Therefore, two assemblies need to be mounted side by side in a common block to measure tilt and displacement simultaneously.

This report describes a ship flexure monitoring system which has been developed to measure four degrees of freedom simultaneously. This system does not measure roll, the fifth degree of freedom; however, by using a polarizer or half-wave plate and detecting polarization changes,[7] roll measurements can be incorporated.

The system consists of a highly collimated laser beam (beam divergence < 0.1 mrad full angle), lenses, a beam splitter, interference

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[1] Carey, G., and P. A. Hickman. "Developments in Laser Alignment Techniques," TRANS ISA, Vol. 9 (February 1970), pp. 222-28.

[2] Cornillault, J. "Using Gas Lasers in Road Works," APPL OPT, Vol. 11 (February 1972), pp. 327-30.

[3] Harrison, P. W. "A Laser-Based Technique for Alignment and Deflection Measurements," CIV ENG PUBLIC WORKS REV, Vol. 68 (March 1973), pp. 224-29.

[4] Skutley, K. "Precision Alignment Systems," CIVIL ENG, Vol. 37 (May 1967), pp. 44-45.

[5] New, B. M. "Versatile Electrooptic Alignment System for Field Applications," APPL OPT, Vol. 13 (April 1974), pp. 937-41.

[6] Burch, J. M., and D. C. Williams. "Afocal Lens System for Straightness Measurement," OPT AND LASER TECH, Vol. 13 (August 1974), 166-68.

[7] King, R. J., and J. W. C. Gates. "Sensitive Method for the Measurement of Small Rotations," J SCI INSTR, Vol. 36 (June 1959), pp. 507-09.

filters, two pin position-sensing photodiode detectors and two displacement monitors. It was designed primarily to calibrate a missile reference system and to measure flexure of a ship in a variety of sea states. The missile reference system consists of two inertial measurement units (IMU) and a software computer algorithm. The algorithm was written such that the outputs of the IMUs were utilized to calculate the motion of the ship. The flexure monitoring system was used to corroborate the data calculated by the algorithm. This report describes only the optical ship flexure monitoring system design and presents some of the results of the optical displacement measurements taken aboard the U.S.S. *Wainwright* (DLG 28).

SYSTEM DESIGN

Consider a simple lens/detector arrangement, shown in Figure 1(a), where the detector, D_1, is in the focal plane of the lens, L_1. In this configuration the detector is insensitive to lateral displacement and sees only an angular displacement, a, which is for small angles

$$a = \frac{d_1}{f_1} \tag{1}$$

where d_1 is the displacement on the detector and f_1 is the focal length of the lens. Under many circumstances the total angular displacement might be extremely small, which indicates that only a small portion of the detector is used. To utilize a larger portion of the detector the focal length needs to be increased; however, it should be increased without significantly increasing the physical size of the system. This can be accomplished as shown in Figure 1(b) with a divergent lens of focal length f_2. Now the angular displacement is given by

$$a = \frac{d_1}{f_1}\left(1 - \frac{f_1 - \ell}{f_2}\right) \tag{2}$$

where ℓ is the distance between lenses L_1 and L_2. This system is still invariant to any lateral displacement. In most applications an interference filter is needed so that the background light does not reach the detector. The interference filter has a thickness, t, and an index of refraction, n, which increases the effective focal length by a factor of

$$\Delta f = t\left(\frac{n - 1}{n}\right) \tag{3}$$

For most cases this factor increases the focal length by 1% or less and is neglected.

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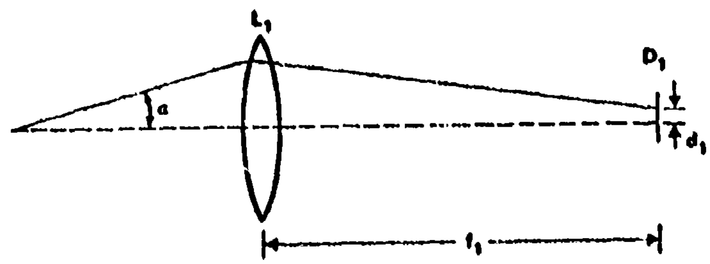
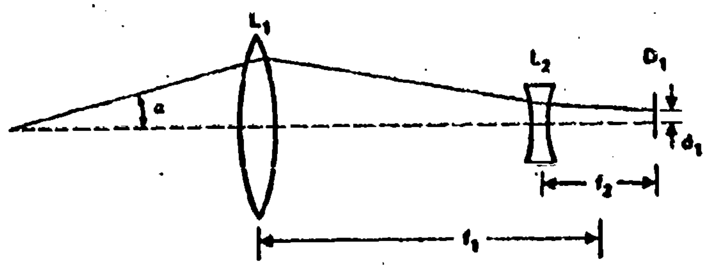


(a) Positive lens with detector at focal plane to measure angular displacements.



(b) Negative lens used to increase effective focal length.

FIGURE 1. Physical Relationship Between Lens and Detector.

Figure 2 shows a lens and detector arrangement which measures both lateral and angular displacement. The lateral displacement, S, is dependent upon α and is given by

$$S = \frac{f_1}{f_3} d_2 - \alpha R \tag{4}$$

where f_1 and f_3 are the focal lengths of lenses L_1 and L_3, respectively, d_2 is the displacement on the detector and R is the separation distance between L_1 and the laser source. As Eq. 4 indicates there exists an ambiguity since the reading of d_2 is dependent upon both S and α. Therefore, by combining the two systems as shown in Figure 3 with a beam splitter, the lateral displacement becomes (for simplicity we will not use the negative lens)

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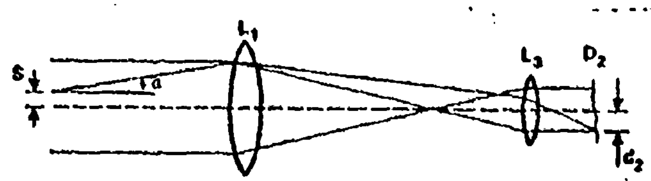

FIGURE 2. Simple Lens System To Measure Both Lateral and Angular Displacements.

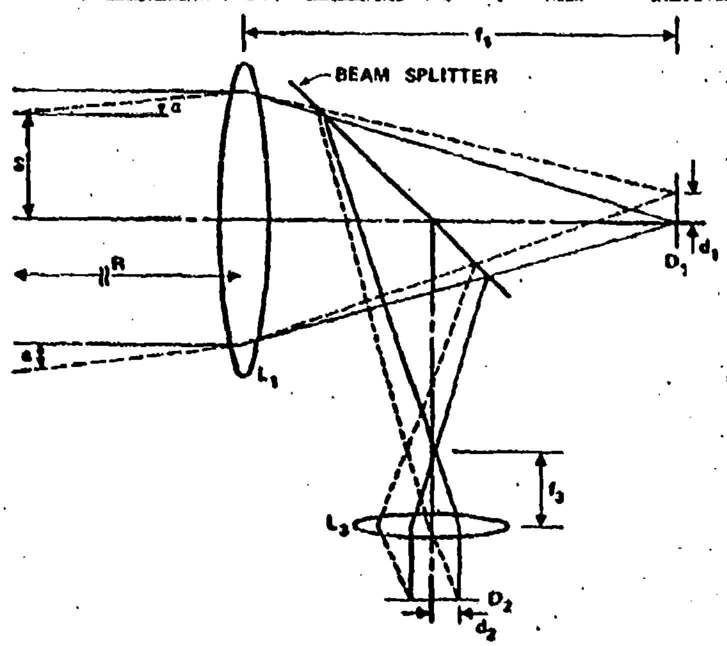

FIGURE 3. Lens System To Measure Both Angular and Lateral Displacement. Beam splitter is used to split 50% of the incoming light.

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$$S = \frac{f_1}{f_3} d_2 - \frac{d_1 R}{f_1} \qquad (5)$$

The beam splitter is of the pellicle type (thickness of 8 microns) so that no unwanted displacement is given due to the thickness of the beam splitter.

The photodiode detectors are a silicon pin-type whose output is proportional to the position of the light impinging on the photodiode. A block diagram[8] of the position displacement electronics is shown in Figure 4. Each displacement monitor has three separate settings for displacement range on the photodiode. The monitors read full scale for a displacement range of ±0.005 inch, ±0.05 inch, or ±0.5 inch. For given focal lengths and maximum angles the system was tested and calibrated for ±0.05 inch full scale. Each photodiode has five connections; the center wire is a bias to the photodiode, two wires are placed along the ± vertical axis and the other two are placed on the ± horizontal axis. The photodiode material has a linear resistivity such that the light striking the photodiode creates electron-hole pairs which causes current to flow in each of the wires which is inversely proportional to the distance from the light. Consequently, the photodiode tracks the position of the centroid of the light. It is very difficult to obtain a piece of silicon which is linear throughout the entire material. Figure 5 displays a linearity curve of the photodiode used in these experiments. The photodiode has a 0.3-inch radius with a linearity of 15% over the 0.3-inch radius; however, if only about 30% of the surface area is used the linearity is 2%. The position-measuring instrument used in these tests has a unique normalization capability. In most other instruments of this kind the output of the photodiode is also sensitive to changes in light intensity. This instrument was designed to have a constant output with a change of an order of magnitude of light intensity; therefore, the system can be used in extreme circumstances where light transmission is a problem.

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[8] United Detector Technology, Inc. *Instrument Manual, Light Position Measuring Instrument*. Santa Monica, Calif., UDT, 10 pp.

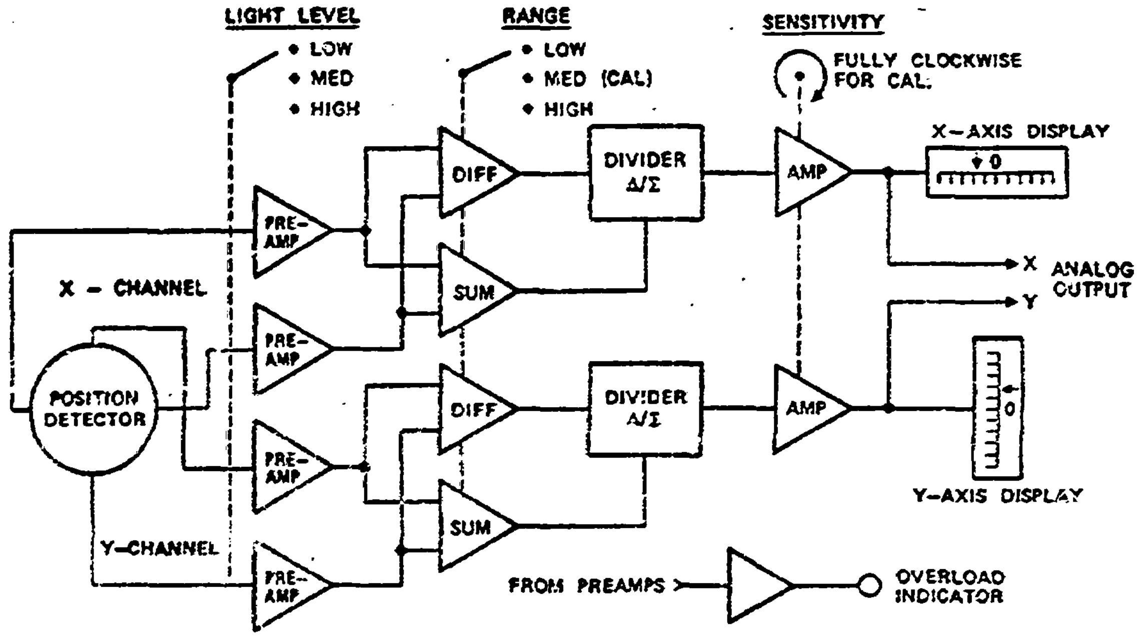

FIGURE 4. Block Diagram of Displacement Monitor Electronics Showing the Sum, Difference and Dividing Networks.

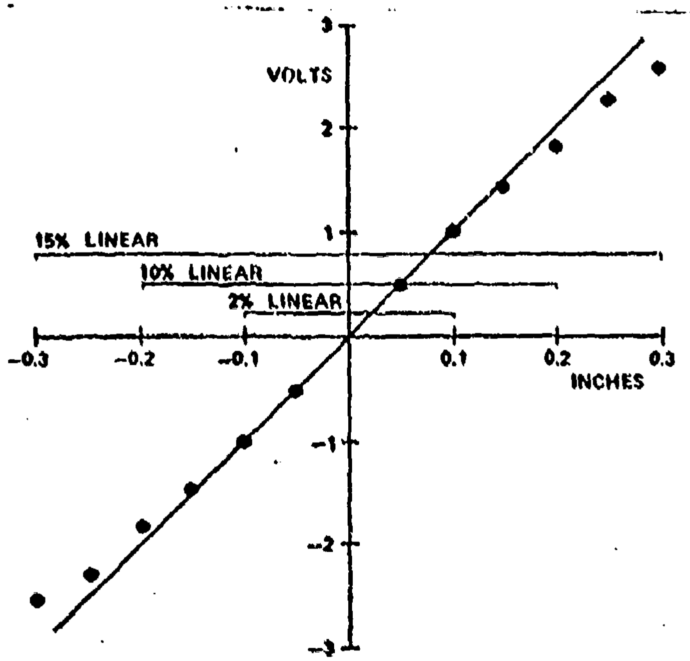

FIGURE 5. Linearity Measurement of the Silicon Pin Photodiode Used in the Displacement Measurements.

MEASUREMENTS

Typical experimental and theoretical curves are shown in Figures 6 and 7. Figure 6 shows the angular displacement data and Figure 7 shows the lateral displacement data; the straight lines are the theoretical curves. Similar data were taken under a variety of circumstances. When the system was given no angular displacement detector 1 (D_1, Figure 3) gave no output and detector 2 (D_2, Figure 3) measured the lateral displacement. When the system was given a fixed angular displacement the lateral displacement was varied, yielding a change in output only from detector 2. When the system was given a fixed lateral displacement the angular displacement was varied. In this case both detectors varied and were in good agreement. In all cases the detectors were in excellent agreement with the known angular and lateral displacement changes. The frequency response of the system is 3 kHz so that there is no problem if the system is to measure rapid displacement changes. The outputs of the instrument provide an analog output of ±5 volts with an output impedance of 1 kΩ.

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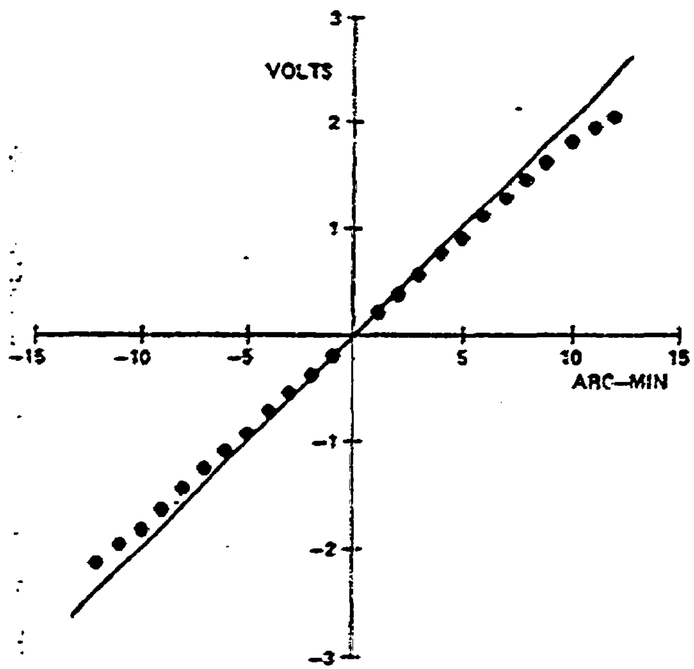

FIGURE 6. Angular Displacement Calibration Measurements Where the Fall-Off of the Larger Angles Is Due to Both the Nonlinearity of the Photodiode and the Lens.

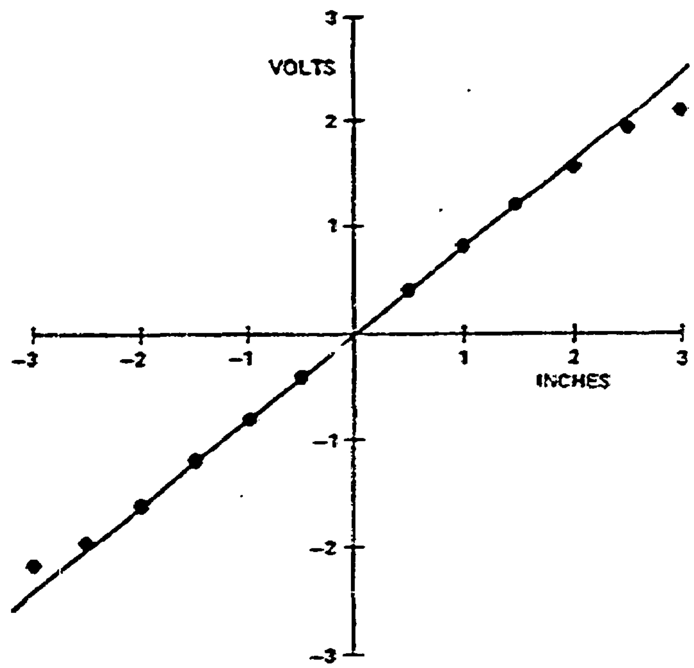

FIGURE 7. Lateral Displacement Measurements Where the Fall-Off at Larger Displacements Is Due to Both the Nonlinearity of the Photodiode and the Lens.

After the system was calibrated in the laboratory it was mounted aboard the U.S.S. *Wainwright*. Figure 8 shows the physical relationship between the laser and the lens/detector assembly. They were mounted across an expansion joint on the ship on the fourth level with a 70-foot baseline. The displacement monitors were strapped on the deck in a watertight container next to the lens system. The linear displacement monitor shown in Figure 9 measures both lateral and angular displacements, and the angular displacement monitor measures only angular displacement. All of the electronics were sealed sufficiently with the only exposed parts being the laser window and the large lens, L_1. The recording equipment was housed in a van two levels down in the helicopter hangar. The recording equipment (Figure 9) consists of an analog tape recorder, oscillograph recorder, an IRIG generator and an oscilloscope. The IRIG generator was used to keep track of the day and time so that the data could be properly analyzed at a later date. The oscilloscope turned out to be very useful because the horizontal and vertical outputs of the displacement monitors were fed to the corresponding inputs of the oscilloscope. This allowed easy visibility of the flexure of the ship; a small dot on the oscilloscope screen moved as the flexure of the ship changed. The oscillograph recorder gave instant flexure measurements. We could easily look at the recorder and tell how much and which direction the ship was flexing. The analog tape recorder was used so that the data could be digitized and plotted upon return from the sea trials.

The first lens was required to be larger than 10 inches in diameter since we were to measure a maximum flexure of 15 arc minutes with a baseline of 100 feet. However, due to unusually calm sea states in the

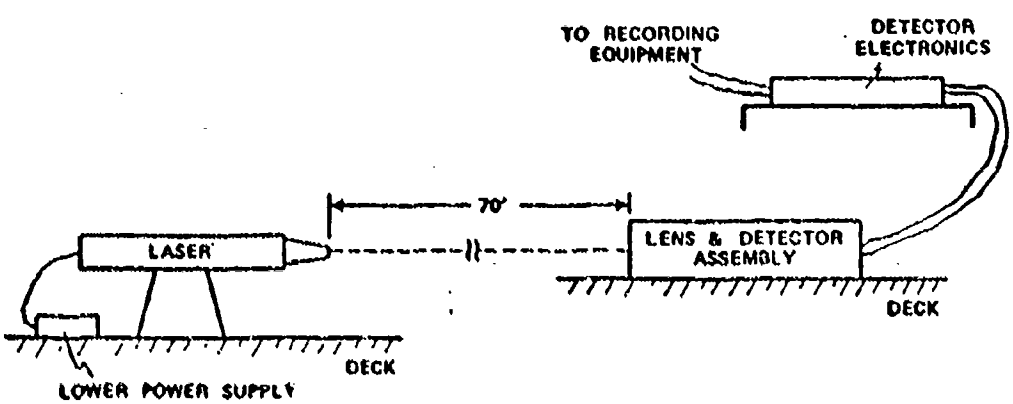

FIGURE 8. Physical Relationship of the Flexure Monitoring System Aboard Ship.

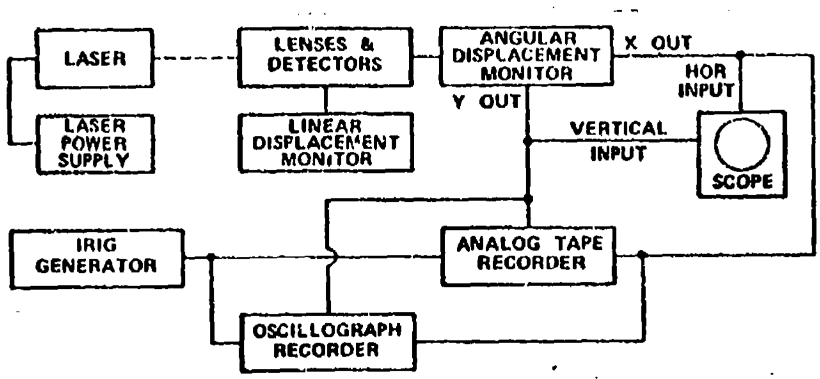

FIGURE 9. Block Diagram of the Equipment Used Aboard Ship To Record the Data Generated by the Displacement Monitors.

North Atlantic in March we did not get much of a variety of flexure measurements. The sea states ranged from no waves at all to waves of about 4 feet in height. Three such angular displacement measurements are shown in Figures 10–12. Both yaw and pitch are plotted over a 1-minute time interval for wave heights 1/2, 3 and 4 feet in Figures 10, 11 and 12, respectively. The data in Figure 10 was obtained while the ship was leaving port and displays a maximum angular flexure of about 1 arc minute, while Figure 11 shows a 2-arc-minute peak flexure and Figure 12 gives a 3-arc-minute peak flexure with a 4.5-arc-minute peak-to-peak flexure. The plots shown in Figures 10–12 were obtained by digitizing the analog tape recorder data. These plots are comparable to those recorded on the oscillograph. The differences between the digitized data and the oscillograph data are explained by the fact that the plots shown in Figures 10–12 were obtained after the analog tape data was transformed to the axis of the ship. We were unable to mount the equipment so that the undeflected laser beam axis was directly down the center axis of the ship. The actual laser beam axis was only slightly off the ship axis; therefore, there are only slight differences between the digitized data and the oscillograph data.

It appears from Figures 10–12 that the yaw and pitch follow each other somewhat, which implies that the ship flexure occurs along some plane and all variations are about this plane. To check this assumption the angle with respect to the vertical was plotted as a function of time. We plotted this only for the data shown in Figure 12; this angle is shown in Figure 13. The average angle measured from vertical about which the ship flexes is 29.8 degrees.

Unfortunately, no meaningful lateral displacement measurements were made due to the malfunction of one of the linear displacement monitors while aboard ship.

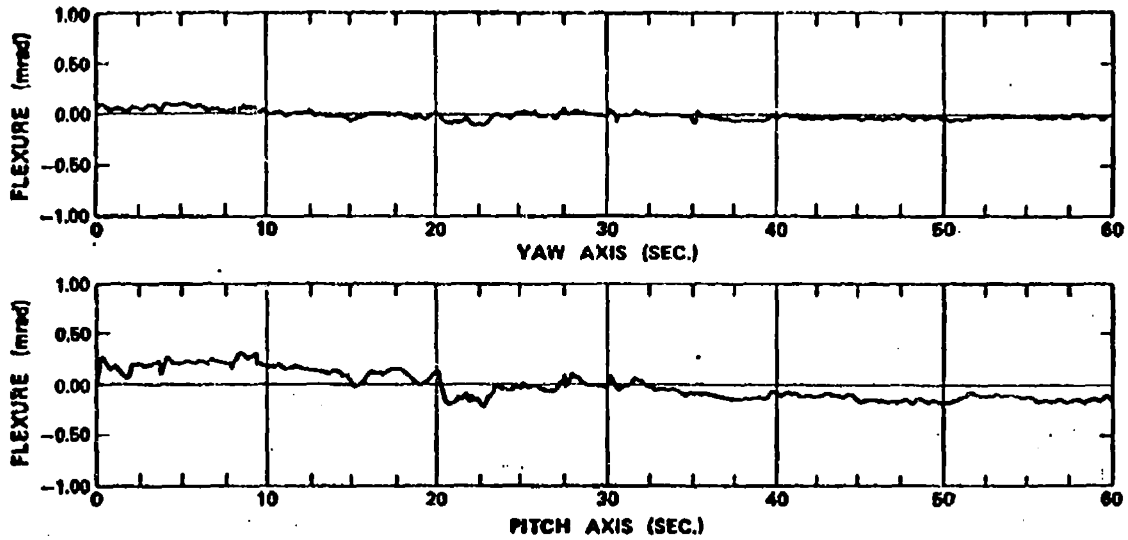

FIGURE 10. Angular Ship Flexure Measurements for a Wave Height of One-Half Foot. Both yaw and pitch are plotted as a function of time.

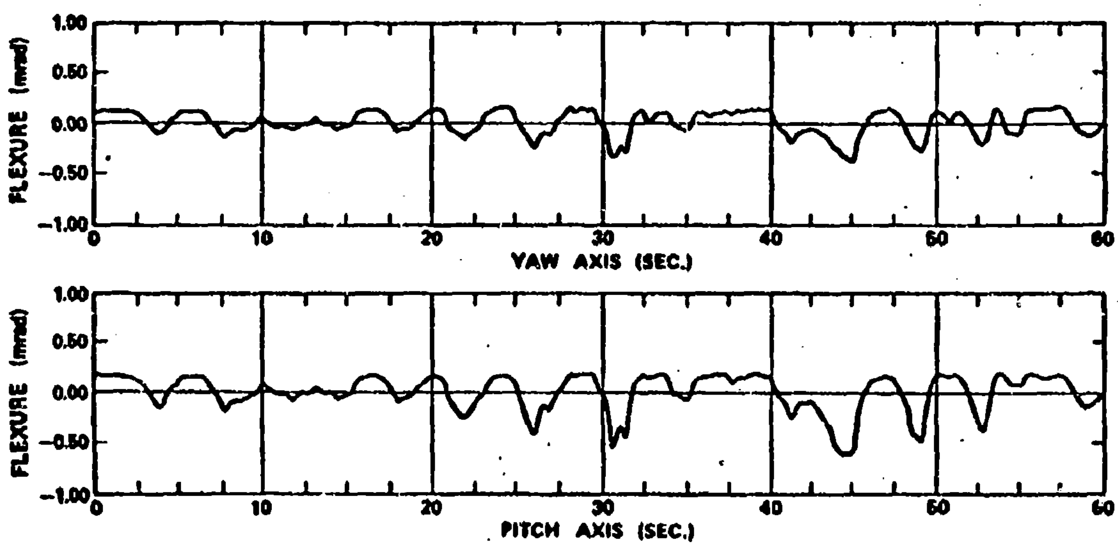

FIGURE 11. Angular Ship Flexure Measurements for a Wave Height of 3 Feet. Both yaw and pitch are plotted as a function of time.

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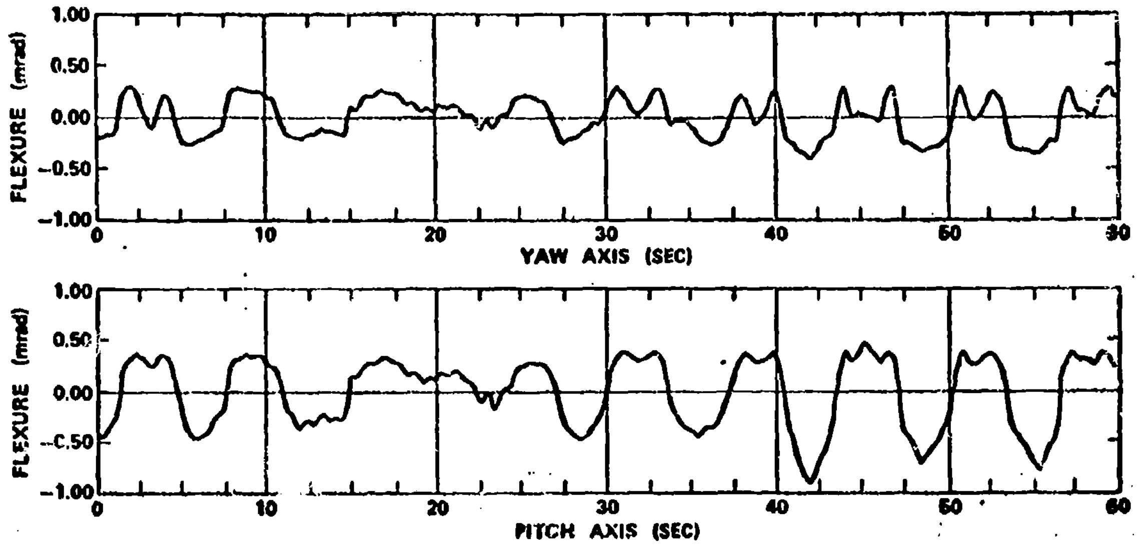

FIGURE 12. Angular Ship Flexure Measurement for a Wave Height of 4 Feet. Both yaw and plitch are plotted as a function of time.

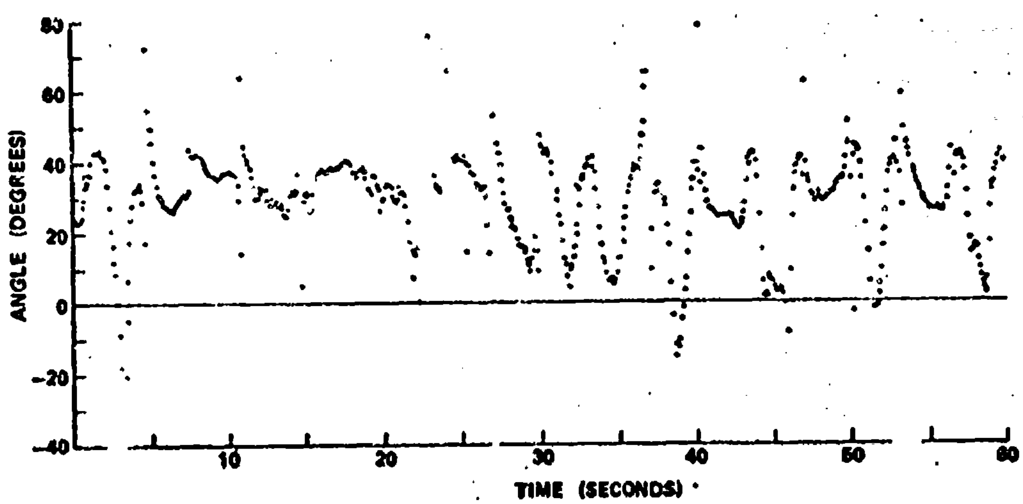

FIGURE 13. Angle of the Plane With Respect to the Vertical at Which the Ship Flexure Occurs Plotted as a Function of Time. Data taken from the angular flexure measurements of wave height of 4 feet. The average angle from vertical about which the ship flexes is 29.8 degrees.

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CONCLUSIONS

The ship flexure monitoring system described here has a problem in that it is extremely sensitive to the placement of the detectors with respect to the lenses. Detector 1 has to be exactly at the focal plane of the lens and if interference filters are used as they were in this system detector 1 has to be shifted even though the increase in focal length is only about 1%. Otherwise, once the detectors, lenses and interference filters are situated in their proper position the system is extremely sensitive and can measure changes on the detector of ±0.001 inch. The system is easy to handle and use after the initial alignment is accomplished.

The ship flexure measurements reported here are not complete since there was very little variety in sea states. The maximum peak flexure measured in these tests was about 3.5 arc minutes during a time when the ship was making sharp turns and maneuvers.